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RELATIONSHIPS BETWEEN RAINFALL AND WEST AFRICAN WAVE DISTURBANCES IN STATION OBSERVATIONS

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ABSTRACT

Morlet wavelets of the meridional component of daily radiosonde wind observations above four West Africa stations were constructed for May–September seasons, 1950–84, at three vertical levels. The passage of African wave disturbances (AWDs) at each station was detected as statistically significant wavelet amplitudes within two spectral bands. The detected AWD activity, or lack of it, was compared with the precipitation record at each station. Results demonstrate that AWDs account for only a proportion of the seasonal rainfall, implying that other precipitation triggers are also important. In addition, the analysis finds that many AWD traversals fail to initiate heavy rainfall at the selected stations. At Niamey, the average precipitation amount per wave had a positive trend between 1953 and 1978. With few exceptions, seasonal precipitation totals were not correlated with the number of days on which AWDs were detected. Although the seasonal average precipitation amount per AWD day exhibited a positive trend at Niamey between 1953 and 1978, there was no corresponding interannual trend in total seasonal precipitation. Copyright © 2003 Royal Meteorological Society.

KEY WORDS: African waves; Sahel rainfall; West African monsoon; wavelets

1. INTRODUCTION

Easterly waves have been identified as a fundamental feature of the synoptic weather regime over West Africa, where they are often called African wave disturbances (AWDs). They are generated from a combination of barotropic and baroclinic instability associated with the African easterly jet at 700–600 hPa and the summertime meridional gradient of lower tropospheric temperatures (Burpee, 1972; Reed *et al*., 1977). Much of West Africa's summer rainfall occurs in organized squall lines (Lamb and Peppler, 1991) and precipitating cloud clusters (Payne and McGarry, 1977) that are imbedded within AWDs (Fortune, 1980; Landsea and Gray, 1992), so it is not surprising that a recent CLIVAR (1999) report suggests that significant interannual climate variations are closely related to the variability of the disturbances. AWD activity is largely confined to the period from May to September and the waves typically have periods between 3–6 days. A second signal with periods between 6 and 9 days in the mid-tropospheric circulation has also been detected over West Africa and the tropical Atlantic (Viltard *et al*., 1998; Diedhiou *et al*., 1999).

Druyan *et al*. (1996) considered the relationship of AWDs to interannual precipitation variability at Niamey, but based on data from only two seasons, 1987 and 1988. They found that some 30% of AWDs traversing Niamey did not produce appreciable precipitation there, and that higher total seasonal precipitation during 1988 was attributable to non-AWD mechanisms. The robustness of these conclusions can only be addressed by the analysis of a much longer record at several locations.

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The current study addresses the relationship between precipitation at four West Africa stations and the characteristics of periodic fluctuations in mid-tropospheric circulation over a span of 35 years, 1950–84. In particular, AWD periodicity is based on time series of the meridional component v of radiosonde wind observations at 850, 700 and 600 hPa above each station.

2. DATA AND METHODS

Data for the current study were obtained from 'Le Service de Météorologie National Française' (1950–65), the National Oceanic and Atmospheric Administration (NOAA) (1964–78), the West African Monsoon Experiment (WAMEX) (1979), and the European Centre for Medium-Range Weather Forecasts (ECMWF) (1980–84). The period of investigation was the summer season (May–September) 1950–84. Daily rainfall data, used to define rainy ($\geq$0.1 mm) and dry days, were supplied by the International Data rescue Coordination Centre (IDCC), Brussels, but for only part of the study period, 1953–78. We consider v time series at 850, 700 and 600 hPa from radiosonde observations at four stations situated between 5 °N and 15 °N in West Africa: Bamako and Niamey are representative of the Sudano–Sahel area, Dakar for the coastal semi-arid zone and Abidjan for the tropical humid climate near the Guinean coast.

Wavelet analysis (Farge, 1992; Torrence and Compo, 1998) is an excellent tool for studying temporal variations of spectral properties in non-stationary time series. Wavelet analysis not only detects periodicities in the time series but it also shows their time dependence. Thus, Diedhiou *et al.* (1999) analysed AWD properties using wavelet analysis of daily 700 hPa v over West Africa from reanalysis data sets for June–September 1988. In the current study, information about periodic fluctuations in v were determined by a similar wavelet analysis. Seasonal wavelet transforms were first examined to determine on which days spectral power was statistically significant at the 95% confidence level (thereby ignoring weaker signals) for each of the two period intervals, 3–5 and 5.5–9 days, and which of the two intervals exhibited the stronger power. Such days on which statistically significant periodic fluctuations of v were detected are referred to below as SPF4 and SPF7 days respectively. Secondly, rainfall time series were examined to determine whether SPF4 and SPF7 days were rainy ($\geq$0.1 mm) or dry. Finally, for each rainy season the total number of SPF4 and SPF7 days was compared with the number of rainy days.

Figure 1(a) shows a sample (1967) time series of v at 700 hPa for Niamey and Figure 1(b) the corresponding wavelet analysis. Derived wavelet amplitudes are taken as evidence of real periodicity if they stand out significantly above a red noise spectrum with 95% or higher confidence with lag −1 coefficient of 0.72. These SPF4 and SPF7 days are outlined by bold contours and generally correspond to high-amplitude fluctuations of v in the time series (Figure 1(a)). Note that significant periodic fluctuations are detected during only parts of the summer. For example, there were 16 SPF4 days in 1967 (18–23 May, 16 July, 13–20 August and 23 August) and 51 SPF7 days (3–24 June, 2–12 August, 25 August to 4 September and 23–29 September). Figure 1(b) also shows that, although both wave periods can be present on the same day, each period band can also occur exclusively on other days.

3. RESULTS

3.1. Partition between different wave periods

As in Figure 1, wavelet analyses of the 700 hPa v at four stations of West Africa during the summers 1953–84 showed a partition of spectral energy between wave periods of 3–5 days and 5.5–9 days. Both signals can occur at significant amplitudes in any part of the summer.

Figure 2 shows the interannual variability of SPF4 and SPF7 days, as well as the total number of days on which *any* significant periodic fluctuations of the 700 hPa v occurred at Niamey. On any given calendar date, fewer than 18 times in 24 summers experienced any significant periodic circulation, fewer than 12 times experienced significant wavelet amplitudes in 3–5 day and 5.5–9 day periods, and for many dates fewer than eight times. A similar partition occurs at the other three stations. The first surge in SPF4 activity occurs at

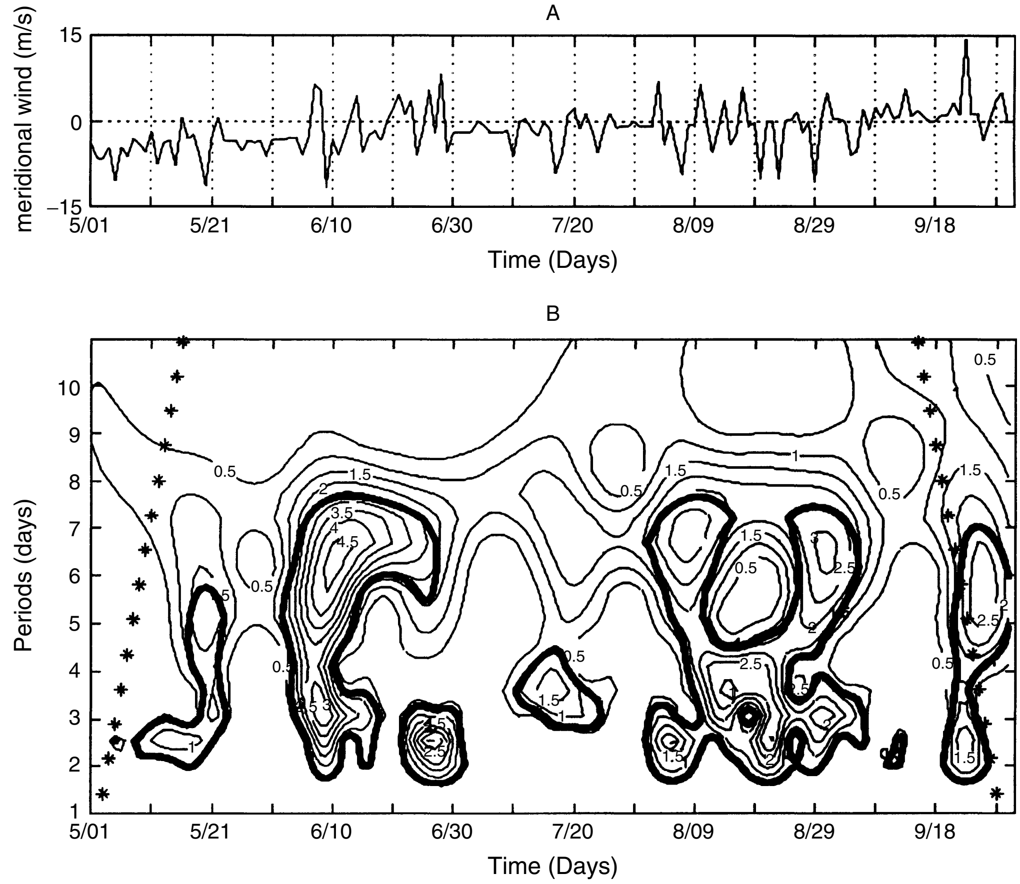

Figure 1. (a) Time series of 700 hPa v for 1 May–30 September 1967 over Niamey. (b) Morlet wavelet amplitudes for the same v time series. The thick contour encloses amplitudes that are statistically significant with 95% or higher confidence for a red noise process with lag −1 coefficient of 0.72. The (∗) denotes the cone of influence beyond which edge effects compromise results. The contour interval is 0.5

the beginning of June, but there are brief periods with a lull in such activity in the second week of June, the second week of July and the last week of August. The frequency of SPF7 during the 24 years studied was not a minimum during the same dates. For example, note the relative maximum of such occurrences during the last week in May, the middle of June and the end of August. Figure 2 also shows that SPF7 days were overall about half as frequent during the 24 years as SPF4, but the relative frequencies vary by date.

SPF4 days are not more frequent than SPF7 days or other periodicities during rainy or drought years. The relative number of SPF4 and SPF7 days varies from year to year, as does the total number of days of significant periodic variability over the entire spectrum.

Table I examines the proportion of the seasonal rainfall accounted for by SPF4 and SPF7 days during all of the years of the study. What is not apparent is that this statistic fluctuated considerably from year to year. For example, at Niamey in 1960, SPF4 days accounted for 90% of the seasonal precipitation, whereas in 1975 such days accounted for only 15%. Table I shows that, at 700 hPa, all of the SPF4 days accounted for only 30–40% of the total rainfall and SPF7 days accounted for 10–20%. Precipitation on all of the days with statistically significant waves of any period was 50–70% of the total. Thus, some 30–50% of the precipitation at the four stations in West Africa was unrelated to periodic circulation features. It is not surprising, therefore, that the analysis presented in Section 3.2 found little or no correlation between the number of days per season with significant periodic circulation and the total seasonal rainfall.

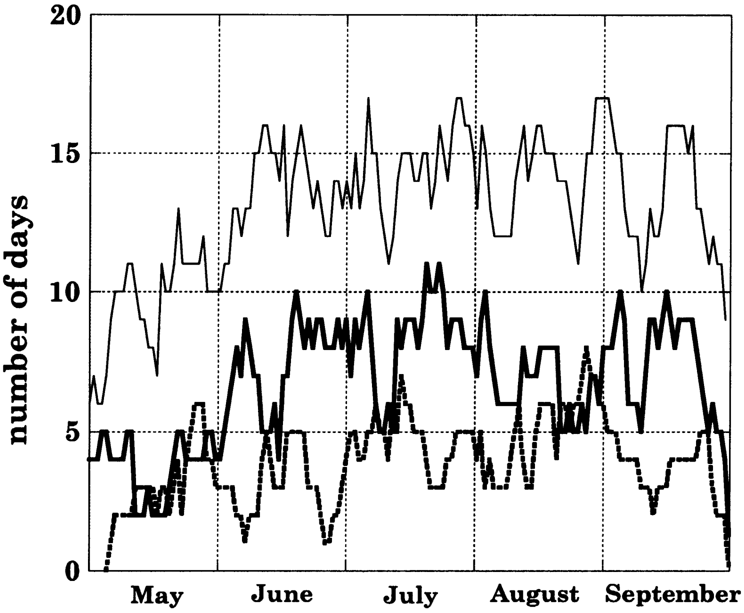

Figure 2. The number of days in 24 years, 1953–78 (1954 and 1963 wind data were unavailable), that experienced periodic circulation of 700 hPa v (thin line), the number of SPF4 days (thick line) and SPF7 days (broken line) at Niamey

Table I. Proportion of the seasonal rainfall, accounted for by days with significant wavelet amplitudes. Wavelets were computed from meridional wind time series at 850, 700 and 600 hPa at Niamey, Bamako, Dakar and Abidjan

Station	Level (hpa)	Seasonal rainfall (%)		
		3–5 days	5.5–9 days	All periods
Niamey (13°30′N, 02°07′E)	850	39.0	15.0	63.4
	700	30.4	17.7	57.8
	600	24.7	14.5	50.5
Bamako (12°08′N, 07°21′W)	850	36.8	14.0	59.3
	700	31.1	9.3	49.2
	600	30.4	11.9	52.4
Dakar (14°44′N, 17°30′W)	850	47.3	12.3	67.2
	700	40.6	19.0	71.5
	600	39.0	17.7	64.7
Abidjan (05°15′N, 03°36′W)	850	34.9	11.9	54.0
	700	35.4	8.6	54.7
	600	33.4	12.0	53.3

3.2. AWD numbers versus precipitation totals

Are seasonal precipitation totals for West Africa related to the periodic fluctuations of the 700 hPa v? The literature relates Sahel precipitation to 3–5 day period waves (Burpee, 1972; Reed *et al.*, 1977). Figure 3 compares the total number of SPF4 days per season in Niamey with the seasonal rainfall for each May–September period. These data were available for the period 1950–84. Overall, there is no correlation between the two statistics. Indeed, two of the four years with fewer than 20 SPF4 days were very rainy (1959, 1967). There are undoubtedly other rain-producing mechanisms operating in this region besides 3–5 day

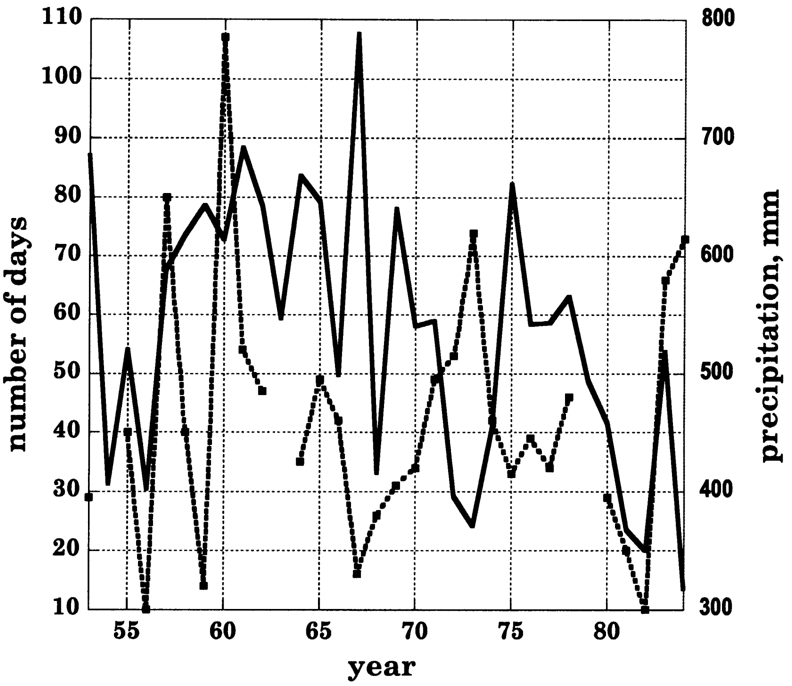

Figure 3. Niamey, seasonal rainfall (black line) and total number of days on which significant amplitudes are computed at 3–5 day periods from the meridional wind time series (broken line). Wind data were unavailable for 1954 and 1963

waves. During 1959 there was a dearth of all wave activity, whereas in 1967 SPF7 occurred on many days (Figure 1). Whether these longer waves explain the large rainfall accumulations is not immediately clear. There were only five seasons with more than 60 SPF4 days: 1957, 1960, 1973, 1983, 1984. However, of these, 1973 and 1984 were extreme drought years, and precipitation during 1983 was near average. This supports the notion that many African wave disturbances lack sufficient moisture to initiate rainfall. There were nine years (not shown) for which there were fewer than 15 SPF7 days: 1955, 1957, 1968, 1969, 1971, 1974, 1981, 1983, 1984. Only three of those years were extremely dry: 1968, 1981 and 1984.

Landsea and Gray (1992) have proposed that a larger number of waves have stronger amplitudes in wet years. We examined the differences in AWD activity between composites of rainy versus dry years at Niamey. Precipitation there exceeded 600 mm for 11 May–September seasons (Figure 3): 1953, 1958–1962, 1964, 1965, 1967, 1969, 1975. Wavelet analysis shows that, during those years, an average of 89 days experienced significant 700 hPa v periodicity within the range of periods up to 9 days. In contrast, during the six seasons of relative drought (precipitation <410 mm: 1956, 1972, 1973, 1981, 1982, 1984) only 73 days on the average experienced significant periodicity of 700 hPa v. Thus, very wet years experienced an average of 16 more days of wave activity than very dry years, but statistical significance cannot be attributed to this difference. Moreover, considering the more classical AWD periodicity, the difference in the average number of SPF4 days for the two composites was a negligible 1.5 days. Correlations between seasonal rainfall and number of days with significant periodicity in v were computed at three vertical levels for all four stations. Table II shows that in almost all cases there is no significant correlation between seasonal precipitation totals and wave activity at any periodicity at any of the three levels.

3.3. Proportion of AWD with precipitation

Table III shows the proportion of SPF4 and SPF7 days that were rainy. Some 55–80% of SPF4 and SPF7 days are dry. Fewer than 30% of the days experiencing AWDs were rainy at Dakar, 36% at Niamey and

Table II. Correlation coefficients between total accumulated seasonal rainfall and total number of days on which significant wavelet amplitudes are computed from meridional wind time series at Niamey, Bamako, Dakar and Abidjan. $R \geq 0.40$ is significant at $\geq$95% confidence level except for Bamako, for which significance requires $R \geq 0.48$

Station	Level (hpa)	R		
		3–5 days	5.5–9 days	All periods
Niamey (13°30′N, 02°07′E)	850	0.12	0.07	0.02
	700	0.14	0.40	0.12
	600	0.36	0.16	0.16
Bamako (12°08′N, 07°21′W)	850	0.10	0.52	0.26
	700	0.11	0.17	0.12
	600	0.17	0.04	0.12
Dakar (14°44′N, 17°30′W)	850	0.16	0.15	0.04
	700	0.25	0.04	0.06
	600	0.30	0.25	0.04
Abidjan (05°15′N, 03°36′W)	850	0.03	0.05	0.02
	700	0.02	0.38	0.32
	600	0.20	0.21	0.03

Table III. Percentage of days with significant wavelet amplitudes on which rainfall was recorded at Niamey, Bamako, Dakar and Abidjan

Station	Level (hpa)	Days of significant wavelet amplitude (%)		
		3–5 days	5.5–9 days	All periods
Niamey (13°30′N, 02°07′E)	850	36.5	34.6	35.7
	700	35.8	38.5	36.3
	600	35.6	34.9	35.7
Bamako (12°08′N, 07°21′W)	850	44.2	41.0	42.9
	700	45.4	40.3	44.5
	600	45.2	44.8	45.9
Dakar (14°44′N, 17°30′W)	850	29.1	23.4	27.3
	700	29.9	24.3	28.2
	600	29.8	21.7	26.4
Abidjan (05°15′N, 03°36′W)	850	45.4	40.2	45.2
	700	45.2	41.0	44.8
	600	44.0	42.9	44.6

45% in Bamako and Abidjan. Thus, some 55–70% of 3–5 day period AWDs that traverse West Africa do not cause precipitation.

Table IV shows that periodic circulation is often missing on rainy days in West Africa ($\geq$0.1 mm). For example, only 50–70% of rainy days at the four West Africa stations experience any strong periodic circulation. Moreover, only 24–45% of rainy days are the result of classical AWDs, identified here as SPF4 days. Note also from Table IV that the frequency of SPF4 and SPF7 for rainy days is much lower than the corresponding frequency for all days.

Thus far, the analysis has failed to produce any compelling statistical evidence that relates AWDs to rainfall amounts in West Africa. It is not surprising that seasons having many days with significant wave activity do not always record excessive precipitation. Nor do seasons having few days with significant wave activity

Table IV. Percentage of rainy days with strong periodic circulation and percentage of all days with strong periodic circulation at Niamey, Bamako, Dakar and Abidjan

Station	Level (hpa)	Rainy days with strong periodic circulation (%)				
		3–5 days		5.5–9 days		All periods rainy
		Rainy	Total	Rainy	Total	
Niamey (13°30′N, 02°07′E)	850	35.9	57.1	16.1	27.1	61.3
	700	29.1	51.6	17.8	29.3	57.1
	600	24.5	48.9	14.5	29.5	50.3
Bamako (12°08′N, 07°21′W)	850	36.6	60.7	14.3	25.7	58.4
	700	30.2	59.3	10.2	22.7	49.8
	600	28.2	53.9	11.7	22.6	53.2
Dakar (14°44′N, 17°30′W)	850	45.5	63.3	14.8	25.7	67.4
	700	40.5	52.2	22.2	35.2	73.4
	600	39.3	52.5	19.5	35.7	66.4
Abidjan (05°15′N, 03°36′W)	850	33.5	61.7	12.8	26.6	54.0
	700	35.5	64.3	10.5	21.0	54.7
	600	34.5	67.6	10.7	21.4	51.8

always experience droughts. Many days with significant wavelet amplitudes do not experience rain and many rainy days occur without any significant wavelet amplitudes. The results described below do, however, suggest that some relationship does nevertheless exist.

Table V examines the relationship between the total number of days experiencing significant wavelet amplitudes versus the total seasonal precipitation accumulation on those same days (days with or without rainfall). This, of course, excludes from consideration precipitation on non-AWD days. The resulting correlation coefficients are reasonably high, e.g. $R = 0.84$, based on 700 hPa v over Niamey, and they suggest that the more AWDs that occur during a given year, then the more total rainfall there will be on

Table V. Correlation coefficients between the total number of days per season experiencing significant wavelet amplitudes versus the total precipitation accumulation on those same days (days with or without rainfall). $R \geq 0.40$ is significant at $\geq$95% confidence level except for Bamako, for which significance requires $R \geq 0.48$

Station	Level (hpa)	R	
		3–5 days	5.5–9 days
Niamey (13°30′N, 02°07′E)	850	0.77	0.72
	700	0.84	0.85
	600	0.83	0.83
Bamako (12°08′N, 07°21′W)	850	0.74	0.90
	700	0.41	0.90
	600	0.80	0.51
Dakar (14°44′N, 17°30′W)	850	0.48	0.36
	700	0.64	0.56
	600	0.74	0.58
Abidjan (05°15′N, 03°36′W)	850	0.56	0.39
	700	0.67	0.61
	600	0.43	0.52

AWD days. If the average precipitation per AWD episode were the same each year, then this correlation would be perfect: $R = 1.0$.

Figure 4 shows the average precipitation per SPF4 and SPF7 day during each season at Niamey. For both spectral intervals, but especially for the 3–5 day period waves, there is an unmistakable upward trend in the average precipitation per episode between 1953 and 1978. For some unknown reason, the average day experiencing wave activity at Niamey was likely to be rainier during the last 10 years. This trend was not detected at the other three stations. In summary, the number of days on which statistically significant wave activity is detected by the wavelet analysis is correlated with the total rainfall on those very same days, although not with the total seasonal rainfall.

4. CONCLUSIONS

Morlet wavelets of the meridional component of daily radiosonde wind observations above four West Africa stations were constructed for May–September, 1950–84, at three vertical levels. The passage of AWDs at each station was detected as statistically significant wavelet amplitudes within two spectral bands identified in the literature: 3–5 day and 5.5–9 day periods. Significant periodic fluctuations detected in each band are referred to as SPF4 and SPF7 respectively. The occurrence of AWDs (SPF4 and SPF7 days) was compared with the precipitation records at each station.

The analysis showed a partition of spectral energy between the two period bands. The relative number of days on which either periodicity is statistically significant varies from year to year, as does the total number of days of significant periodicity over the entire spectrum. On any given summer day there is less than a 50% probability of SPF4 at Niamey. At the four locations included in the study, SPF4 days accounted for only 30–40% of the total rainfall and SPF7 days accounted for 10–20%. Some 30–50% of the precipitation at the four stations in West Africa was unrelated to periodic circulation features detected by the wavelets.

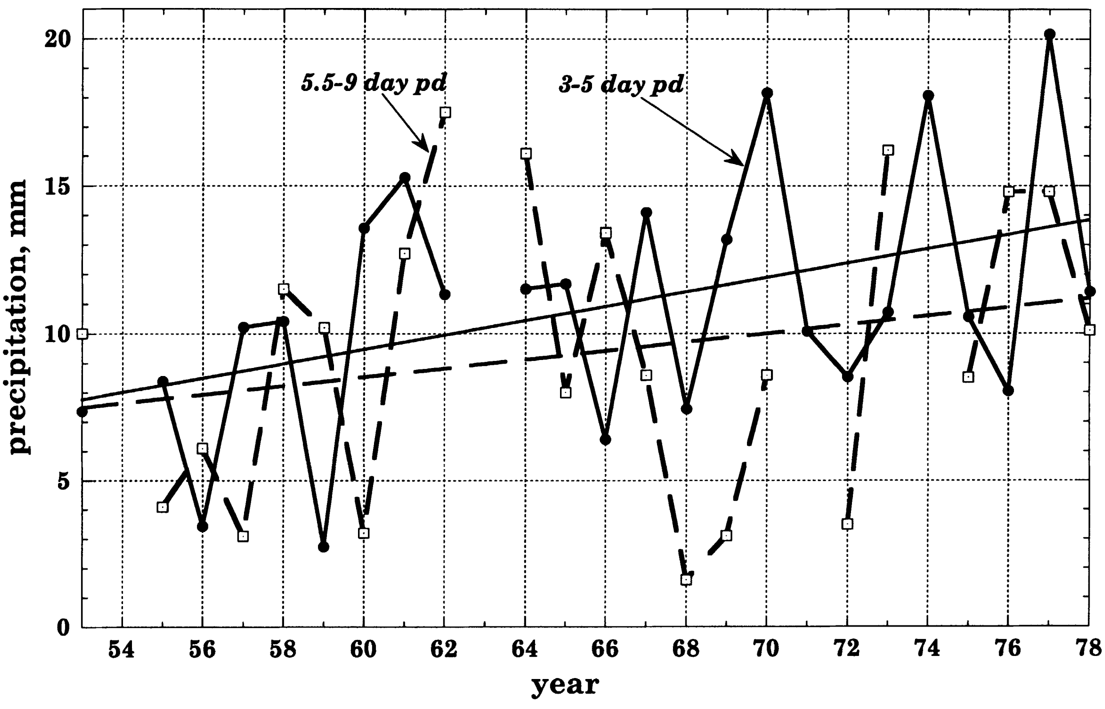

Figure 4. Seasonal averages of precipitation per wave day for significant 3–5 and 5.5–9 day periods of 700 hPa meridional wind over Niamey and best linear fit to each series. Wind data were unavailable for 1954 and 1963. In 1971 and 1974 there were no SPF7 days

The average number of days at Niamey experiencing significant periodicity of 700 hPa v was lower for a composite of the driest seasons than for the alternative composite of the most rainy seasons; but, with few exceptions, the seasonal total precipitation accumulation at each station was uncorrelated with the number of SPF4 or SPF7 days at 850, 700 or 600 hPa. There are several examples of drought years with many AWDs and of rainy seasons with relatively few AWDs. The highest correlation coefficient (0.52) between precipitation totals at Bamako and the number of SPF7 days based on the meridional wind at 850 hPa above the station was significant at the 95% confidence level.

At Niamey, the seasonal average precipitation per SPF4 and per SPF7 day varied from 2–20 mm. A positive trend of this statistic was detected in the Niamey data between 1953 and 1978, but not at the other three stations. During the 1970s, the average precipitation per SPF4 day was always at least 8 mm and it was more than 17 mm for three of those seasons. There was no corresponding parallel trend in total seasonal precipitation. At all four stations, the precipitation total on all such days was correlated with the number of SPF4 and SPF7 days in any given season.

The current study has identified the passage of AWDs based on a significance test of wavelet amplitudes. This method uses a rather high threshold and could have missed some AWDs identifiable by other means. This is especially true during intervals experiencing a high variability of the meridional wind. Moreover, since precipitation rates in and around AWDs can fluctuate during the lifetime of these transient easterly waves, examination of this association at fixed locations probably also underestimates the number of AWDs that organize heavy rainfall during their complete trajectory, which sometimes crosses 30° or more of longitude. These caveats notwithstanding, it is clear from the results that the seasonal statistics of AWDs at a station give no unambiguous indication about the seasonal precipitation. Moreover, though squall lines and convective complexes associated with AWDs are important, they are not exclusive mechanisms for precipitation over the summer monsoon areas of West Africa.

ACKNOWLEDGEMENTS

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